Response to Reviewer Comments

This study entails the critical role of understanding drought impacts on environmental flows and contributes valuable insights into preserving the ecological integrity of rivers in the Indus Basin. In this study, the authors use a combination of various methods for analyzing drought and environmental flows. Their aim to inform and facilitate sustainable water resources management practices is vital in the region. With the projected increase in the frequency of future extreme droughts in the Indus catchment, this study could add valuable insights in understanding environmental flows in the catchment and be a good addition to the scientific literature. However, less focus should be put on the drought events and drought severity in the catchments (because this is already known in literature) and more on the novelty of the study which is the influence of drought on the magnitude of the extreme low flows and low flows. I suggest some improvements detailed below, that may help in bringing this message out more clearly before the manuscript can be viable for publication. I hope my comments can contribute to enhancing the quality of the paper.

Response: Authors are thankful to the valuable comments from reviewer that helped in substantially improving the quality of the manuscript. The comments are incorporated into the manuscript (can be seen through track changes) and response of each comment is given here in blue color.

Major Comments:

1. First of all, the question of uncertainty in the datasets, and the IHA model used should be discussed in the discussion section. How this would have impacted the analysis? I understand that the research idea is to understand how droughts influence extreme low flows and low flows, but perhaps more details on the different methods used could be given in the methodology, for example, how did you select the threshold for the threshold regression analysis, what does the coefficient value represent and also further elaboration on the steps involved in the implementation of the range variability analysis could be provided instead of a list. Generally, the methodology on range variability analysis and threshold regression analysis could be elaborated further to enable easier understanding on the methods, i.e., methods for performing threshold regression analysis is a bit lacking hence when one reaches the results section, understanding becomes difficult.

Response: The analysis to understand uncertainty in collected data including in-situ precipitation and temperature data are already carried out by the authors in previously published manuscripts, and also the descriptive statistics of the data is given in the supplementary file to this manuscript. Data processing before carrying out the analysis is described in Lines 156-161 (in the revised manuscript, the same below). Some of the insights into data quality and IHA analyses are further discussed in the discussion section.

This research is mainly devoted to understand the impact of drought on environmental flow, where threshold regression is a robust technique to understand the impact of drought on environmental flow as threshold regression not only identifies the drought severity but also the time when drought has resulted in significant decline of flow in major rivers of the Indus Basin. The advantages and effectiveness of threshold regression over other change-point analysis method are already discussed in details in Lines 248-258.

We add more explanation on the results of threshold regression analysis: The coefficient in Table 3 quantifies the impact of drought on environmental flow. For instance, the threshold regression in Gilgit catchment shows that drought has a significant impact (0.949) on environmental flow during the period of 1992-2011. During the mentioned period, Indus Basin has experienced frequent extreme drought events which not only impacted the surface water availability but also other sectors including agriculture (Rahman et al., 2023). It should be noted that the coefficient of SPEI-1 varies significantly from one catchment to another and from one period to another during to significant variations in climatic and land use characteristics accompanied with frequent fluctuations in SPEI-1 estimates (Lines 379-384).

The threshold regression is run under two different scenarios to understand what is the magnitude of drought that causes the extreme low flows and low flows, and when (time) the drought resulted in extreme low flows and low flows. Explanation to these points is already given in lines 333-337.

2. Secondly, the authors performed further data quality tests on the hydro-meteorological datasets, i.e. using kurtosis and skewnesss, these plots could be included in the supplementary materials, this may help with the question on uncertainty of the datasets. For example, Line 144: The authors state that the data was thoroughly analyzed and the period from 1980-2018 chosen. How was this analysis carried out? Additionally, the authors failed to discuss the limitations of the research and future recommendations. How does this research compare to other studies done in

the Indus catchment? Generally, the discussion of the results could be improved and line 496-506 could be moved to introduction.

Response: The descriptive statistics of the kurtosis and skewness results are given in a Tables S1 and S2, which clearly depicts that data is normally distributed. The data is then used to calculate the drought indices SPEI.

Explanation is added to line 144: After thoroughly analyzing all the collected data (i.e., checking the date/years of available data at most of the in-situ stations), a period from 1980–2018 is chosen to demonstrate the drought impact on environmental flow where all the in-situ stations have the data with few or no missing values (Lines 150-152).

Limitations of the research and future recommendations are added in the discussion section (Lines 522-533).

The original Lines 500-505 were moved to the introduction section (Lines 75-79).

3. On a side note, the authors could try using threshold-based indices instead of the standardized indices. This is to explicitly bring out the roles of temperature and precipitation on the occurrence of droughts and then make the conclusion on influence of temperature on drought occurrence as done in line 516: 'The analyses have shown that temperature plays a crucial role in the occurrence of droughts'.

Response: The authors have used the most commonly used standardized drought index (i.e., SPEI) to monitor droughts' impact on environmental flow. The use of SPEI for this purpose is of significant importance as several studies have estimated drought using SPEI. Further, the National Disaster Management Authority (NDMA) of Pakistan recommended SPI and SPEI to monitor drought in Pakistan. Therefore, this study has used SPEI to analyze the impact of drought on environmental flow, which can be easily interpreted and help policy makers to devise a policy that mitigates the impact of drought on environmental flow. Authors have published several manuscripts that highlighted the role of temperature on the occurrence of drought events over the Indus Basin. Moreover, this study also highlighted that as we move from UIB to LIB, the frequency and severity of drought significantly increase which substantially reduced the environmental flow.

References:

Ur Rahman, K., Shang, S., Balkhair, K. and Nusrat, A., 2023. Catchment-Scale Drought Propagation Assessment in the Indus Basin of Pakistan Using a Combined Approach of Principal Components and Wavelet Analyses. Journal of Hydrometeorology, 24(4), pp.601-624.

Rahman, K.U., Hussain, A., Ejaz, N., Shang, S., Balkhair, K.S., Khan, K.U.J., Khan, M.A. and Rehman, N.U., 2023. Analysis of production and economic losses of cash crops under variable drought: A case study from Punjab province of Pakistan. International Journal of Disaster Risk Reduction, 85, p.103507.

Hussain, A., Jadoon, K.Z., Rahman, K.U., Shang, S., Shahid, M., Ejaz, N. and Khan, H., 2023. Analyzing the impact of drought on agriculture: evidence from Pakistan using standardized precipitation evapotranspiration index. Natural Hazards, 115(1), pp.389-408.

4. Additionally, in the results section, it is hard to differentiate what is moderate and what is extreme drought because this is not indicated. What is considered a low flow and extreme low flow? Is it possible to provide specific values for these magnitude of the low and extreme flows associated with each of the drought severities?

Response: Drought severity is divided into several categories (a standardized procedure followed in several manuscripts) based on the SPEI values. In this revised version, we have added the SPEI ranges of drought severity classes in Lines 186-187 and Table S3.

The flow is considered low flow when the magnitude of flow is less than 25th percentile (Kumar et al., 2022). In this study, when the magnitude of flow is less than 10th percentile, we classified it as extreme low flow. The division of flows into different classes and their ranges are given in Lines 200-203.

"IHA categorizes streamflow into several components, including low flows (where the streamflow values are less than or equal to 25th percentile), moderate flows (where the streamflow values range between 26th to 75th percentile) and high flows (where the streamflow values are greater than 75th percentile). Besides, when the flow is less than the 10th percentile, we classified it as extreme low flow".

5. In general, the quality of the writing and preparation should be improved. I found it hard to continuously scroll up to always look for the full meaning of the abbreviations. It is good

practice to state the full abbreviations again especially when it comes at the beginning of the paper. What I would suggest to the authors is that they carefully review the text to avoid several grammar errors and typographical errors prevalent in the manuscript.

Response: The abbreviations are checked and listed at the end of the manuscript. Moreover, the manuscript is carefully checked and revised to remove grammatical and typographical errors.

6. Line 165: How did the authors calculate the potential evapotranspiration or actual evapotranspiration used in the water balance equation?

Response: SPEI calculation is usually based on potential evapotranspiration, which can be calculated using several methods, including Thornthwaite, Penman-Monteith, and Hargreaves. However, we have used Hargreaves equation in this method to calculate potential evapotranspiration as it requires less data (Hargreaves and Samani, 1985). The remaining methods are based on extensive data including solar radiation, relative humidity, and wind speed, which is mostly not available in the Indus Basin. Therefore, Hargreaves method is suggested by several authors when other data is not available (Abbasi et al., 2021; Allen et al., 1996; Dubrovsky et al., 2009).

References:

Hargreaves, G.H. and Z.A. Samani, Reference crop evapotranspiration from temperature. Applied engineering in agriculture, 1985. 1(2): p. 96-99.

Dubrovsky, M., M.D. Svoboda, M. Trnka, M.J. Hayes, D.A. Wilhite, Z. Zalud, and P. Hlavinka, Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia. Theoretical and Applied Climatology, 2009. 96: p. 155-171

Abbasi, A., K. Khalili, J. Behmanesh, and A. Shirzad, Estimation of ARIMA model parameters for drought prediction using the genetic algorithm. Arabian Journal of Geosciences, 2021. 14(10): p. 841.

Allen, R.G., Assessing integrity of weather data for reference evapotranspiration estimation. Journal of irrigation and drainage engineering, 1996. 122(2): p. 97-106.

7. Line 178: How did the authors come to this choice of threshold value?

Response: Drought severity, as mentioned above, is divided into several classes, including normal (wet/drought events) with SPEI values ranging between 1 to -1. To avoid the frequent normal events, we have considered a threshold of SPEI < -1 (Table S3).

8. Line 215-line 216: This statement doesn't make sense. Do you mean the no drought years are pre-impact and drought years post-impact? How did you come to select SPEI-12 for the analysis? Isn't that double counting or rather counterintuitive cause the drought years are already in the pre-impact period, if the whole period was considered? How does this impact your results? Or did you remove the drought years? If yes, then state this instead of saying the whole period was considered as pre-impact period.

Response: RVA is typically used to understand the post-impact of any alteration in streamflow, where the entire period is divided into pre- and post-impact periods on the representing the streamflow before and after the alteration, respectively. In the current study, we considered the impact of drought by comparing the entire period (1980–2018) with specific drought years (i.e., years/representative drought years where the SPEI values are less than -1) to understand how drought events causes alterations in streamflow. The statement about SPEI-12 is revised as "To investigate the impact of drought on environmental flow in the current study, the whole period (1980-2018) is considered a pre-impact period (without differentiating between drought and wet events, which can also be considered as normal flow years without focusing on specific drought years), while the specific drought years (i.e., where the average SPEI values are less than -1, also considered as representative drought years as identified by Rahman et al., 2023a and 2023bSPEI-12 < -1) are considered a post-impact period" given in lines 228–232.

In the whole period, we have considered the streamflow from 1980–2018 without differentiating between streamflow during drought and wet years. In other words, the pre-impact period is equivalent to the streamflow without differentiating between drought or wet periods. In contrast, if we consider the years excluding drought years, it will not meet the conditions of pre-impact period as mentioned in the RVA guidelines.

9. Line 221: The numbers are very specific, is this based on something? If that is the case please cite or if not give reasons for the categories division

Response: HAF values are already defined in the literature by Ritcher et al. (1997). Citation is added to the lines as suggested (Line 235).

Minor Comments:

1. The authors should carefully review the text to avoid several grammar errors and typographical errors prevalent in the manuscript for example;

Response: The manuscript is checked for grammatical errors and typos as suggested.

2. In Figure 1, it would be better if the authors combine the legends so you have a single legend to indicate the basin names.

Response: The Figure 1 shows four different aspects of the Indus Basin; (a) elevation, (b and c) the location of rainfall/temperature and flow gauges along with the demarcation of Upper, Middle, and Lower Indus Basins, and (d) sub-division of the three basins into different catchments. For better representation of the catchments, the number along with specific names of the catchment is given separately. Therefore, it is better to represent different aspects of the Indus Basin separately.

3. Line 260: I would suggest to mention the list of names based on the figure alignments.

Response: Corrected as suggested.

4. Line 279: It would be clearer if the authors indicated these years on the plots, otherwise it becomes difficult to look for the specific years within the each of the plots. I would suggest to do the same for figures 3-5.

Response: Corrected as suggested.

5. Figure 4: Use the same scale for all the plots. It becomes quite confusing when they have different scales for example first look makes me think that Hunza catchment droughts are more severe. I would suggest to do the same for the rest of the plots (figures 3-5, 6).

Response: Corrected.

6. Line 294: I think this statement should be moved to the case study section.

Response: We think this statement is a continuation of previous statements and do not move it to the case study section.

7. Line 364: Jhelum Rive is also divided into three time periods

Response: Corrected.

8. Line 358: As a reader, I find using the term time zones confusing, is there a better term that could be used instead? e.g. time period?

Response: Time zones are replaced with time periods as suggested.

9. Table 2: Is it possible for the authors to Separate the catchments to UIB, MIB and LIB, otherwise one keeps going up to the case study section to check which catchments are where. Additionally, is it possible to indicate the specific thresholds for extreme low flows and low flows instead of combination?

Response: Table 2 is revised as suggested; however, it is not possible to specify separate thresholds for extreme low flows and low flows as threshold regression separates/identifies on time period from another on the basis of a specific threshold (i.e., sudden shock or break in the time series) irrespective of the magnitude of streamflow provided. We will consider this problem in further studies.